

Effect of a cement-lignin agent on the shear behavior of Shanghai dredged marine soils

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ABSTRACT

With the rapid urbanization in Shanghai, China, suitable fill materials have been reported to be in great shortage in recent years. A prospective solution to these issues is to convert the huge amount of existing dredged marine soils to construction materials via solidification. However, there have been no studies on the shear behavior of the SDMs from Shanghai region so far, while it has been reported by many other researchers that the available data obtained from certain types of clay cannot be confidently and readily applied to other types of soils. To address this challenging issue, in this paper, samples of Shanghai marine dredged soils were retrieved from the world's largest reclamation project in Shanghai Lin-gang New City. A series of laboratory tests have been conducted to investigate the shear behavior of Shanghai dredged marine soils solidified using a new composite curing agent (PM) made of cement and lignin. The test results and the effect of this cement-lignin agent on the shear behaviour of Shanghai marine soils, including the stress-strain behavior, shear strength properties and failure characteristics has been presented and discussed, which can provide valuable reference for the use of dredged soils as construction materials in the Shanghai region.

Key words: dredged materials; soft soil; composite cement agent; laboratory tests; Shanghai region; solidification.

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1. Introduction

In recent decades, due to drastically increased demand of maritime transports for international and domestic trades, a huge amount of investment has been made by the Chinese government on the construction of marine infrastructures, such as ports, waterways etc. As a result, an unexpected amount of dredged materials (DMs) was produced during the construction of such structures as well as the maintenance of the existing shipping channels. Yet, as these DMs are very soft with very limited strength and high compressibility (Chiu et al. 2009), they cannot be reused directly as geo-construction materials. Thus, in China, DMs have always been treated as geo-waste and directly dumped into the ocean, resulting in unforeseen large volume of DMs accumulated in the ocean. It is statistically reported that the annual production of DMs in the only Shanghai region exceeds 70 million m³, and so far more than 2.5 billion m³ of DMs had been already dumped into the surrounding ocean (Jiang et al., 2013; Wang et al., 2013). Such uncontrolled and unsustainable offshore dumping of dredged soils has posed a serious threat to natural coastal and marine ecosystems and raised great concern among many researchers, practicing engineers and the Chinese government (Dai, 2005; Zhu et al., 2005a,b; Feng et al. 2007; Jin et al., 2009; Ding et al., 2012). Given the aforementioned reasons, it is therefore urgent and imperative to find an alternative, effective and sustainable solution to the hazardous offshore disposal of DMs.

A potential solution to such an urgent issue is to convert very soft DMs via solidification (Huang et al., 2011). Solidification of soft clayey soils including marine clayey DMs by using cement, to create improved materials with better geotechnical properties, has proved to be effective and sustainable (e.g. Bergado et al., 1996; Uddin et al., 1997; Tremblay et al., 2001; Horpibulsuk et al., 2003, 2004; Lorenzo and Bergado, 2004; Kasama et al., 2006; Åhnbergh, 2007). Nevertheless, it has been emphasized by a number of studies (e.g., Nagaraj and Miura, 2001; Sasanian 2011) that the available data obtained from certain types of clay cannot be confidently and readily applied to other types of soils, such as dredged marine silty soils.

Recently, the mechanical properties of solidified inland soft soils have been extensively studied by many researchers in China (e.g. Gao and Li, 1996; Zheng et al., 2002; Chen, 2011). In contrast, even

though the need for improving and reusing soft DMs as effective construction material has been highlighted by the Chinese government (Zhu et al., 2005; Feng et al., 2007; Shao et al., 2007; Ding et al., 2010), comprehensive studies on the properties of the solidified marine silty DMs with extremely low strength and relatively high compressibility are still rather limited. In addition, most of the existing studies on SDMs have been mainly focusing on unconfined compression strength (e.g. Tang et al., 2000), which would not represent the more general in-situ stress conditions. Therefore, shear properties of marine SDMs subjected to different stress paths should be investigated before recommend of its utilization for many geotechnical applications, such backfill material, embankment and highway subgrade soil etc.

The world largest land reclamation project in Shanghai Lin-gang New City (located in the Pudong district of Shanghai) was initiated in 2003 and is expected to be completed by 2020. Despite an investment of over 40 billion Chinese dollars to create more than 130 km² of land by offshore expansion, suitable fill materials have been reported to be in great shortage (Wang et al., 2013). A prospective solution to such a matter is to improve the locally abundant soft silty DMs via solidification and reuse them as proper fill materials. However, as to the knowledge of the authors, there have been no studies on the shear behavior of the SDMs from Shanghai region so far, while it has been reported by many other researchers (Nagaraj and Miura, 2001; Sasanian 2011) that the available data obtained from certain types of clay cannot be confidently and readily applied to other types of soils

In this context, in this paper, the marine silty DMs collected from east coast of Shanghai Lin-gang New City (Fig. 1) were solidified using a new composite curing agent. Two series of monotonic undrained triaxial tests were performed on the SDM specimens sheared under two different stress paths (i.e. constant cell pressure and conventional triaxial and constant mean stress). Test results were systematically analyzed in terms of shear resistance, deformation behavior and failure characteristics. The encouraging results obtained from this study may provide a good reference for many geotechnical researchers and engineers dealing with the reuse and recycling of DMs via solidification for many practical applications, especially in the Shanghai region of China.

2. Experimental program

2.1 Tested materials

In this study, marine DM samples were collected from a site located on the Eastern coast of Lin-gang New City in Shanghai, which is located in the peninsula between the Yangtze and Qiantang Rivers, on Hangzhou Bay and it is approximately 60 kilometers Southeast of downtown Shanghai (point A in Fig. 1).

Marine DM, named hereafter as Shanghai DM, can be classified as silty soils. A typical particle gradation curve and index properties are reported in Fig. 2 and Table 1, respectively. Shanghai DM has a relatively high water content of 40%, liquid limit of 34.5%, plastic limit of 27.1 % and plasticity index of 7.46. Therefore, it is essentially a silt with low/intermediate plasticity.

A composite curing agent, called PM curing agent, attained by combining cement and a new activator, was used to stabilize (solidify) the Shanghai DM. The major constituent of the activator is lignin, which is a complex phenolic polymer made from the polymerization of aromatic alcohol. Compared to the traditional cement agents, the PM agent is more effective for the solidification of unstable soils, especially DM with high water content (Jiang and Liu, 2013).

2.2. Specimen preparation and testing procedure

When SDM cures for a period of time it forms a soil structure. The main strength source of SDM is from cementation bonds (Horpibulsuk et al., 2004). To evaluate the performance of PM as a curing agent for the solidification of DMs, soil samples were mixed with different percentages (by weight of the soil) of PM (i.e. 0%; 4%; 5%; 6%; 7%). Following the recommendations made by Burland (1990), a soil vibrating mixer was used to mechanically mix the dredged soil with the PM curing agent until a uniform slurry was attained. The dredged materials obtained from the site were then placed into a stainless steel cylindrical mold 38 mm in diameter and 76 mm in height. The vibration method was used to prevent air entrapment during the preparation process, which was conducted at room temperature. The specimens were then sealed by plastic wrap and soaked/cured in water in a humidity controlled room at a constant

temperature ($20 \pm 2^\circ \text{C}$) for 28 days (Fig. 3). To simulate the field conditions as much as possible, seawater obtained from the Eastern coast of Lin-gang New City was used in this study. The chemical composition of the seawater is reported in Table 2.

After confirming Skempton's B -value of 0.97 or above (i.e. fully saturation), several specimens were isotropically consolidated increasing the total mean stress (p) up to 100 kPa, 200 kPa and 300 kPa. Then, undrained monotonic shearing was applied, at a deformation rate of 0.073 mm/min, following two different triaxial stress paths (i.e. conventional triaxial compression tests (CTX) and triaxial compression test with constant mean stress (PTX)). In the CTX tests, the specimens were loaded axially up to failure by increasing gradually the axial stress (σ_a) while keeping constant the cell pressure or more specifically the radial stress (σ_r), as reported in Table 3. Alternatively in the PTX tests, the specimens were loaded axially by increasing gradually σ_a and decreasing simultaneously σ_r in order to maintain constant the total mean stress (p) (Table 3).

These two different stress paths i.e. CTX and PTX were chosen to investigate the SDM response under the stress conditions for highway subgrade soil as well as embankment and slope, respectively. The initial void ratio and confining pressure conditions for both series of CTX and PTX tests are listed in Table 4.

3. Results of conventional triaxial compression (CTX) tests

Typical CTX test results are presented and discussed hereafter in terms of stress-strain relationships, triaxial stiffness or elastic moduli, failure modes and shear strength characteristics.

3.1. Stress-strain response

Fig. 4 presents deviator stress vs. axial strain relationships for non-solidified DM specimens (i.e. PM=0%) compared to the solidified counterpart with increasing percentages of PM curing agent (i.e., 4%, 5%, 6% and 7%) under various initial total mean stresses (i.e., $p_0 = 100$ kPa, 200 kPa and 300 kPa). In the case of the non-solidified DM specimens, the stress-strain curves show a typical strain hardening response (i.e. deviator stress increases continuously with axial strain) irrespective of the level of applied p_0 .

Significantly, the values of deviator stress at peak stress state (q_{peak}) are relatively low being approximately 163 kPa, 292 kPa and 409 kPa for $p_0 = 100$ kPa, 200 kPa and 300 kPa, respectively. From a practical viewpoint, this implies that non-solidified Shanghai DMs cannot be directly used as construction materials for geotechnical applications, unless effectively improved.

Significantly, it is observed that q_{peak} increased substantially when DM specimens are cured by using various percentages of PM cement agent. For instance, in the case of PM = 7%, q_{peak} of solidified specimens increased up to approximately 765 kPa, 932 kPa and 1114 kPa for $p_0 = 100$ kPa, 200 kPa and 300 kPa, respectively.

To better describe the effects of PM content on SDM shear strength improvement, a coefficient K_q is defined in this study as the ratio between $q_{\text{peak,PM}}$ of the solidified specimens and reference $q_{\text{peak,0}}$ of non-solidified DM specimens:

$$K_q = \frac{q_{\text{peak,PM}}}{q_{\text{peak,0}}} \quad (1)$$

As shown in Fig. 5, within the range of pressure and percentage of PM investigated, K_q seems to increase exponentially with the addition of PM curing agent to DMs. It can be also observed that the improvement is more significant for the specimens consolidated under a lower p_0 of 100 kPa. For example, by using PM = 7%, the shear strength of the solidified dredged specimen under $p_0 = 100$ kPa was approximately 4.5 times greater than that of the non-solidified counterpart, while under $p_0 = 300$ kPa was only 2.6 times greater than the non-solidified dredged specimens. To capture such behavior, based on the findings, an empirical correlation is proposed to evaluate K_q as a function of both initial mean stress (p_0) and the amount of PM (in %) used to solidify Shanghai DMs:

$$K_{q(\text{CTX})} = (0.868 + 0.0002 p_0) \exp[(0.265 - 0.0004 p_0) \text{PM}] \quad (2)$$

Furthermore, it can be seen from Fig. 4 that with the addition of PM, the behavior of SDM change gradually from strain hardening to strain softening, since a clear drop of the deviator stress is observed after reaching a peak value. Therefore, in general solidified Shanghai DM specimens behave more brittle than those non-solidified showing a more ductile response.

To evaluate the observed change in failure behavior from ductile to more brittle, Fig. 6 reports the change in axial strain (ϵ_a) measured at q_{peak} for SDM specimens solidified by using a different percentage of PM (4-7%). It clearly appears that ϵ_a decreased significantly with the increasing percentage of PM. In the case of PM = 4%, ϵ_a was approximately 2.9%, while ϵ_a decreased to 1.3% for PM = 7%. Alternatively, no significant effect of p_0 is observed on the brittleness since a unique curve is obtained for specimens sheared under various p_0 levels. More details about failure modes for SDM is provided afterward.

3.2. Deformation modulus

As shown in Fig. 4, the monotonic triaxial stress-strain response of SDM is clearly non-linear. However, for design purposes, a convenient parameter namely the triaxial loading stiffness or deformation modulus (E_{50}) can be determined from the triaxial stress-strain curves for a mobilization of 50% of the maximum shear strength at failure q_{peak} . For that reason, Fig. 7 shows the effect of PM content on the change in E_{50} for various SDM specimens. Similarly to q_{peak} , for the range of PM percentage examined, E_{50} also seems to increase exponentially with increasing addition of PM for all levels of initial p_0 . For PM=7%, E_{50} of solidified dredged soil increased up to approximately 80 MPa, which is approximately 15 times greater than that of the untreated counterpart (i.e. ≈ 5 MPa). From a practical viewpoint, this finding is important because it implies that Shanghai SDMs has potential to be used as an effective geo-construction material. Following, a useful empirical correlation is proposed to estimate E_{50} for a given PM content (in %) and p_0 level:

$$E_{50(CTX)} = (1.48 + 0.003p_0) \exp(0.5PM) \quad (3)$$

3.3. Shear strength characteristics

In accordance to the theory of Mohr's circle of stress, the shear strength parameters (i.e., cohesion c and friction angle ϕ') of non-solidified DM and its solidified counterpart were determined. In Fig. 8, the obtained values of c and ϕ' are plotted against the PM content. A significant and non-linear increase in c

due to the addition of PM content is observed (Fig. 8a). Specifically, using PM=7%, c of SDM specimens increased up to approximately 185 kPa, which is over 12 times greater than that of the non-solidified counterpart. Such behavior can be represented by the following empirical correlation:

$$c_{(CTX)} = 12.118 \exp(0.385 PM) \quad (4)$$

It is also found that ϕ' considerably increases with the percentage of PM from 22.3° for non-solidified DM specimens to 28.0° for SDM specimens containing PM = 7% (Fig. 8b). A linear empirical correlation between ϕ' and PM content is proposed by fitting the experimental data:

$$\phi'_{(CTX)} = 22.329 + 0.812 PM \quad (5)$$

3.4. Failure characteristics

In Fig. 9, failure characteristics are reported and compared for treated and non-treated specimens (i.e. PM = 0, 4%, 5%, 6% and 7%) for the case of $p_0 = 100$ kPa. Clearly there is a change in the failure mode from shear failure (ductile-type) to tensile-crack (brittle-type). In particular, for PM=0% (i.e. untreated DM), a distinct failure plane with orientation of about 60° can be observed (Fig. 9a). Alternatively, for PM = 4%, some minor cracks occurred even though the specimen still failed along a shear failure plane (Fig. 9b). This behavior may be attributed to some tensile stress developed in the specimen, which developed as a result of the addition of PM. Yet, it was not significant enough as compared to the shear stress component, thus, leading to the failure of the specimen along the shear plane with small cracks. However, when the addition of PM increased up to 5%, additional small cracks developed in the specimen compared to the case of PM = 4%. Nevertheless, no clear failure plane was observed. This is due to the fact that the tensile strength of the specimen was significantly improved after solidification by PM, promoting quick development of small cracks in the specimen during shearing process and a more brittle failure-type (Fig. 9c). In contrast, for PM=6% and 7%, the specimens broke with bigger cracks (Figs. 9d and 9e), which is closely consistent with the observed stress-strain curves as shown in Fig.4. The SDM exhibited a significant brittle behavior. That is, when PM curing agent was added into soils in the presence of water,

the reactions between agent and dredged soil particles caused an increase in soil rigidity that caused the development of a more brittle behavior of SDMs.

4. Results of constant mean stress triaxial compression (PTX) tests

A second series of consolidated undrained triaxial compression tests (PTX) was performed by keeping constant the total mean principal stress (p) throughout the shearing process. Typical PTX test results are presented and discussed hereafter.

4.1. Stress-strain behavior

Fig. 10 presents the deviator stress vs. axial strain curves for non-solidified (i.e. PM=0%) and solidified (PM = 4 - 7%) Shanghai DM specimens sheared at a constant mean stress of 100 kPa, 200 kPa and 300 kPa. Similar to CTX tests, in the case of PTX, the stress-strain curves reveal a strain hardening response of non-solidified DM specimens irrespective of the level of applied initial p_0 . The values of deviator stress at q_{peak} are relatively low being approximately 107 kPa, 210 kPa and 372 kPa for $p_0 = 100$ kPa, 200 kPa and 300 kPa, respectively. Nevertheless, the addition of PM curing agent significantly contributed to the increase in q_{peak} . For example, for PM=7%, q_{peak} increased up to approximately 653 kPa, 818 kPa and 1001 kPa for $p_0 = 100$ kPa, 200 kPa and 300 kPa, respectively.

This is confirmed by looking at the variation in the coefficient K_q , as shown in Fig.11. It is observed that within the range of PM content and p_0 investigated, K_q seems to increase exponentially with the addition of PM. In particular, a substantial increment was observed beyond PM=4%. Eventually, by using PM = 7%, the shear strength of the solidified dredged specimen under $p_0 = 100$ kPa was approximately 6 times greater than that of the non-solidified counterpart. Such an improvement in K_q is more significant for the case of SDM specimens sheared under a constant p_0 of 100 kPa, compared to those sheared at a higher p_0 of 200 kPa and 300 kPa. The proposed empirical correlation to evaluate K_q as a function of PM content and p_0 in PTX tests is as follows:

$$K_{q(PTX)} = (0.886 + 0.0003 p_0) \exp[(0.329 - 0.0006 p_0)PM] \quad (6)$$

Furthermore, Fig. 12 shows the change in axial strain (ϵ_a) evaluated at q_{peak} state for all specimens sheared at a constant p_0 . Similar to the observations in CTX tests, in PTX tests significant decrease in ϵ_a is observed with increasing percentage of PM, implying that the solidified dredged specimen behave progressively more brittle.

4.2. Deformation modulus

The effect of PM on the change in E_{50} for all specimens sheared in PTX tests under a constant- p_0 condition is presented in Fig. 13. Irrespective of the p_0 level, a significant improvement in E_{50} of the SDM specimens can be observed. For PM=7%, E_{50} increased up to approximately 70 MPa, which is approximately 14 times bigger than that of the untreated counterpart (i.e. ≈ 5 MPa). In addition, it appears clear the effects of PM content are more significant than the effects of p_0 on the change in E_{50} properties. This is described by the following empirical correlation to estimate E_{50} for a given PM content (in %) and p_0 level:

$$E_{50(PTX)} = (1.25 + 0.003 p_0) \exp(0.5 PM) \quad (7)$$

5. Comparison between CTX and PTX test results

Overall, Shanghai SDM specimens show a lower q_{peak} value when sheared under constant mean stress conditions (PTX tests) than when sheared under constant cell pressure conditions (CTX tests), as presented in Fig. 14. This is essentially due to the fact that in PTX tests, in order to maintain mean stress constant, the cell pressure is progressively reduced throughout the shearing process, and thus such a lower soil shear strength is feasible.

Nevertheless, the addition of PM significantly improved the SDM peak shear strength in both CTX and PTX test. Interestingly, comparing Figs. 5 and 11, it can be seen that such an improvement is more prominent in the case of PTX tests compared to CTX tests. Also, it appears that the development of shear

strength due to PM is more effective at lower mean stress levels.

By looking at the value of axial strain at peak deviator stress state (Figs. 6 and 12), it appears that Shanghai SDM shows similar failure behavior under both CTX and PTX testing conditions.

Similar values of shear strength parameters, such as c and ϕ' , were also found to be very similar under CTX and PTX conditions.

6. Summary and conclusions

In this study, an attempt was made to assess the suitability of SDM for use as geo-material for backfills, embankment and highway subgrade. A series of triaxial tests under two different stress path conditions (i.e. constant cell pressure (CTX) and constant mean stress (PTX)) were conducted on samples solidified by using a new composite curing agent made of cement and lignin. Based on experimental results, the following main conclusions can be drawn:

1. Under both CTX and PTX conditions, stress-strain curves of non-solidified DM specimens are characterized by a relatively low peak shear strength (q_{peak}), irrespective of the level of initial mean stress (p_0) applied. From a practical standpoint, this implies that non-solidified Shanghai DMs cannot be directly used as construction materials for geotechnical applications, unless effectively improved.
2. With the addition of 4-7% PM (percentage based on dry weight), after the 28-day curing period, q_{peak} drastically increased, thus enabling Shanghai SDM to be used as an effective geo-construction material. For instance, for PM=7%, q_{peak} increased up to 4.5 times in CTX tests and up to 6 times in PTX tests with respect to the case of non-treated DM.
3. The deformation modulus (E_{50}) also significantly increased by using PM curing agent confirming the effectiveness of such treatment for improving the geotechnical properties of investigated Shanghai DM. For PM = 7%, E_{50} of SDM specimens increased from ≈ 5 MPa to approximately 80 MPa in CTX tests and 70 in PTX tests, which is approximately 14-15 times greater than that of the untreated counterpart.

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4. The addition of PM = 7% to Shanghai DM also contributed to a significant increase in both the cohesion (from 12 kPa to approximately 180 kPa) and the friction angle (from approximately 22° up to 28°).
 5. Non-treated DM showed a typical shear failure along a well-defined plane. In contrast, due to the fact that the tensile strength of the specimen was significantly improved after solidification by PM, the development of small cracks and a more brittle failure-type was observed in the case of the solidified specimens. That is, when the PM curing agent was added to soils in the presence of water, the reactions between agent and dredged soil particles caused an increase in soil rigidity that improves the brittleness of soils.
 6. In general Shanghai SDM showed a similar behavior when sheared under constant cell pressure (CTX tests) or constant mean stress (PTX tests) conditions. However, compared to CTX tests, it is observed that the in PTX tests solidified DM specimens tend to show a lower peak resistance and shear strength. This is due to the fact that, in PTX tests, the confining pressure is decreased to keep the total mean stress constant during the shearing process. However, results from PTX tests can be useful in many practical cases where the total mean stress is likely to be constant throughout the shearing process.

38 To confirm the encouraging experimental finding above described, the authors are currently conducting
39 field investigations to evaluate the actual load-deformation response of Shanghai SDM to further enable
40 the use of such SDM for large reclamation projects in the Shanghai region. The encouraging results
41 obtained from this study may provide a good reference for many geotechnical researchers and engineers
42 dealing with the reuse and recycling of DMs via solidification for many practical applications, especially
43 in the Shanghai region of China.
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Table 1
Index ad physical properties of investigated Shanghai dredged marine soils

Specific gravity, G_s	2.71
Unit weight, γ (kN/m ³)	19.6
Moisture content, w (%)	40
Liquid limit, w_L (%)	34.5
Plastic limit, w_P (%)	27.1
Plasticity index, I_p	7.46

Table 2
Chemical composition of seawater retrieved from Hangzhou bay

Chemical components	NaCl	MgCl ₂	MgSO ₄	CaSO ₄	K ₂ SO ₄	CaCO ₃
Concentration (g/l)	27.2	3.8	1.7	1.2	0.9	0.1

Table 3

Stress paths employed in this study for monotonic CTX and PTX shearing tests

Stress components	CTX ($\sigma_r = \text{constant}$)	PTX ($p = \text{constant}$)
Total mean principal stress	$p = \frac{\sigma_a + 2\sigma_r}{3}$	$p = \frac{\sigma_a + 2\sigma_r}{3}$
Deviator stress	$q = \sigma_a - \sigma_r$	$q = \sigma_a - \sigma_r$
Increment of axial stress	$d\sigma_a > 0$	$d\sigma_a > 0$
Increment of radial stress	$d\sigma_r = 0$	$d\sigma_r = \frac{-d\sigma_a}{2}$
Increment of mean principal stress	$dp = \frac{d\sigma_a}{3}$	$dp = 0$
Increment of deviator stress	$dq = d\sigma_a$	$dq = \frac{3}{2}d\sigma_a$

Table 4

Initial testing conditions for both series of CTX and PTX tests

Initial total mean stress p_0 (kPa)	Percentage of curing agent PM (%)	Initial void ratio e_0
100	0	0.612
100	4	0.629
100	5	0.635
100	6	0.641
100	7	0.645
200	0	0.596
200	4	0.610
200	5	0.614
200	6	0.622
200	7	0.628
300	0	0.588
300	4	0.594
300	5	0.596
300	6	0.608
300	7	0.612



Fig. 1. Location of sampling site for Shanghai DM investigated in this study

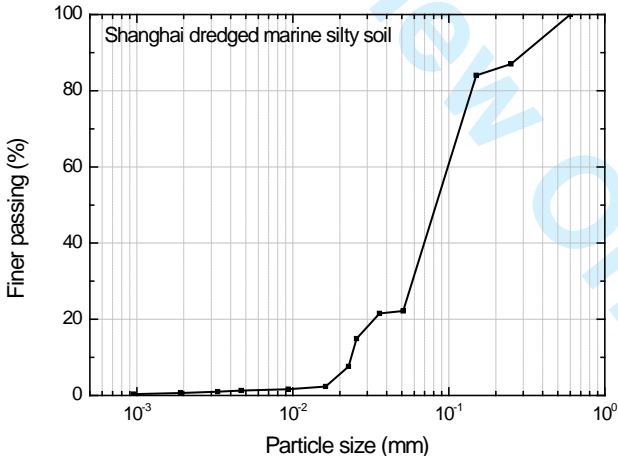


Fig. 2. Particle size distribution curve for investigated Shanghai DM

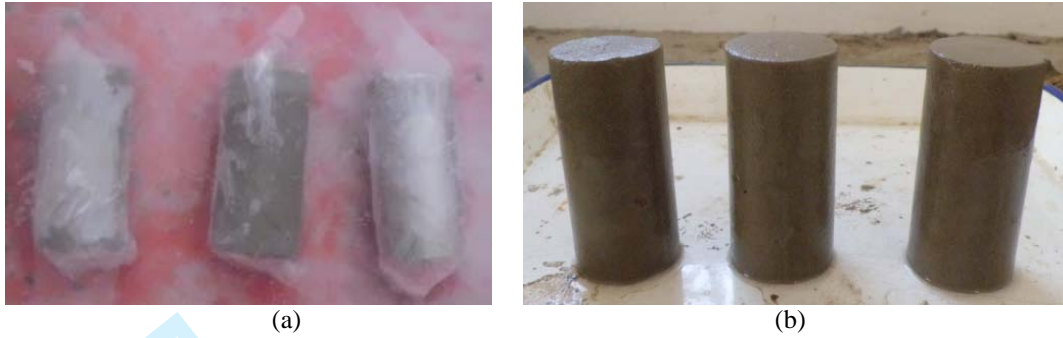


Fig. 3. Shanghai DM solidified by PM curing agent: (a) specimens while soaking in a water bath to cure at a constant temperature ($20\pm 2^{\circ}\text{C}$); and (b) specimens after 28-day curing period

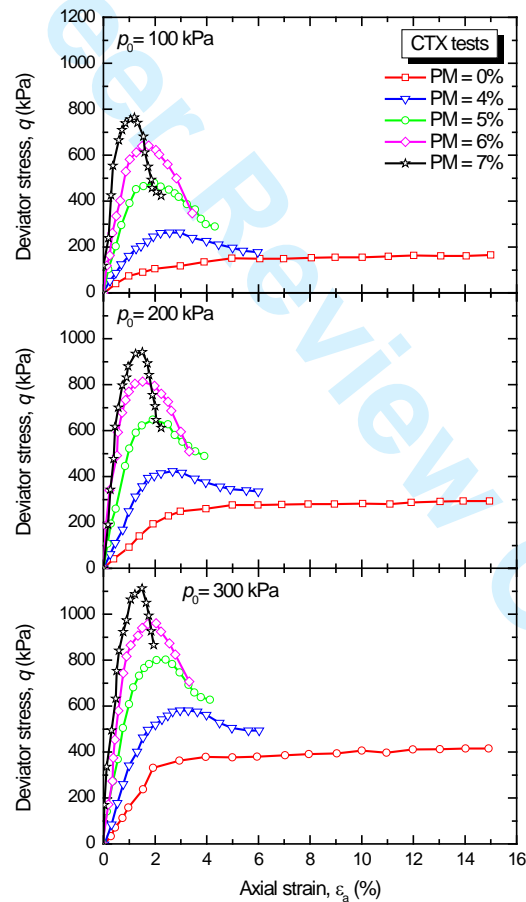


Fig. 4. Stress- strain relationships of non-solidified and solidified by PM Shanghai DM specimens in CTX tests

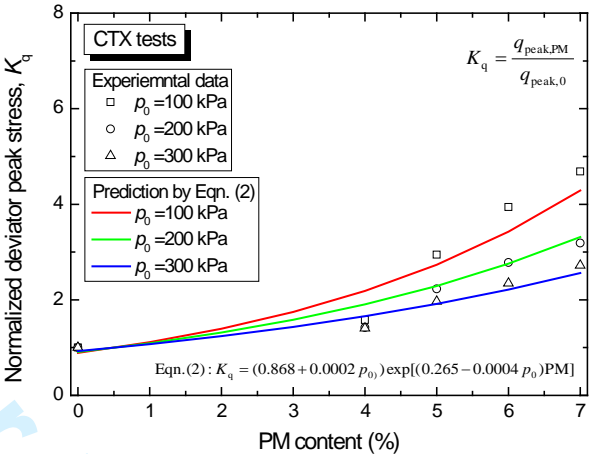


Fig. 5. Normalized peak deviator stress for Shanghai SDM in CTX tests

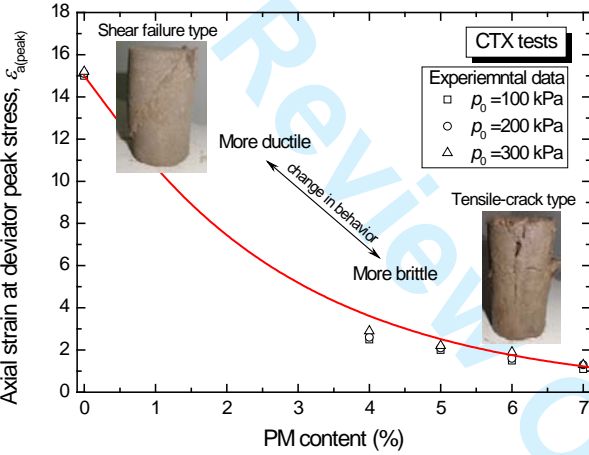


Fig. 6. Axial strain at peak deviator stress for Shanghai SDM in CTX tests

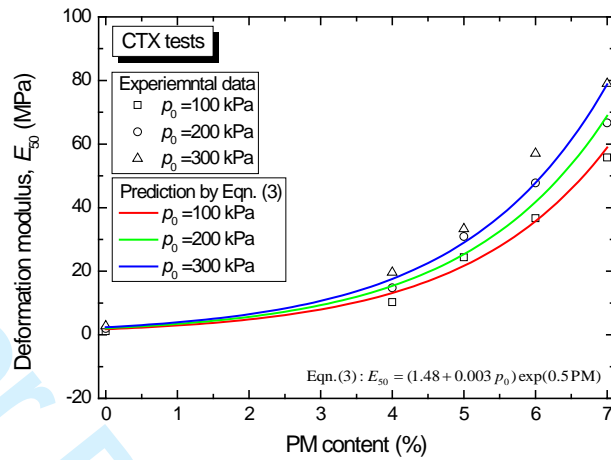


Fig. 7. Deformation modulus (E_{50}) for Shanghai SDM in CTX tests

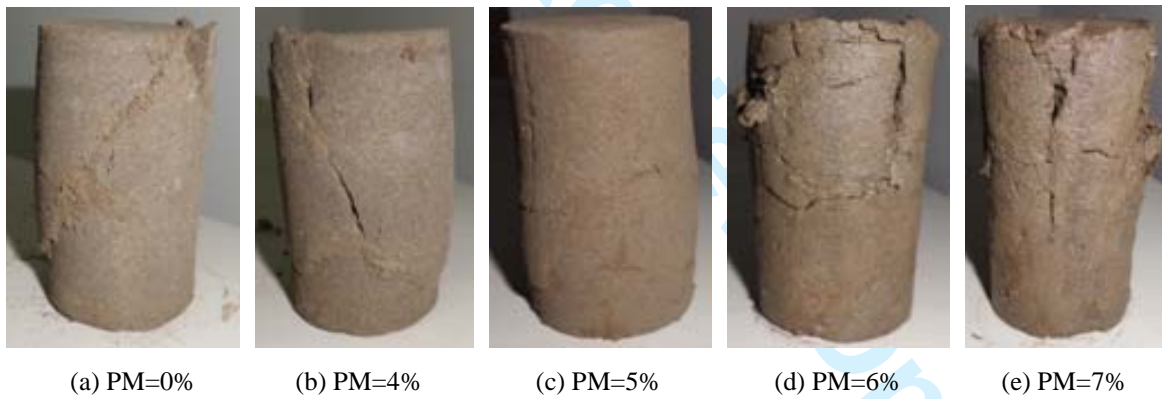


Fig. 8. Failure modes for Shanghai SDM specimens in CTX tests

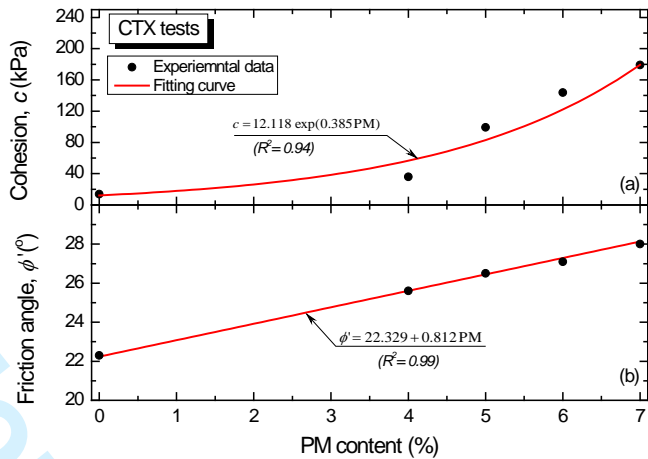


Fig. 9. Variation of shear strength parameters for Shanghai SDM specimens in CTX tests

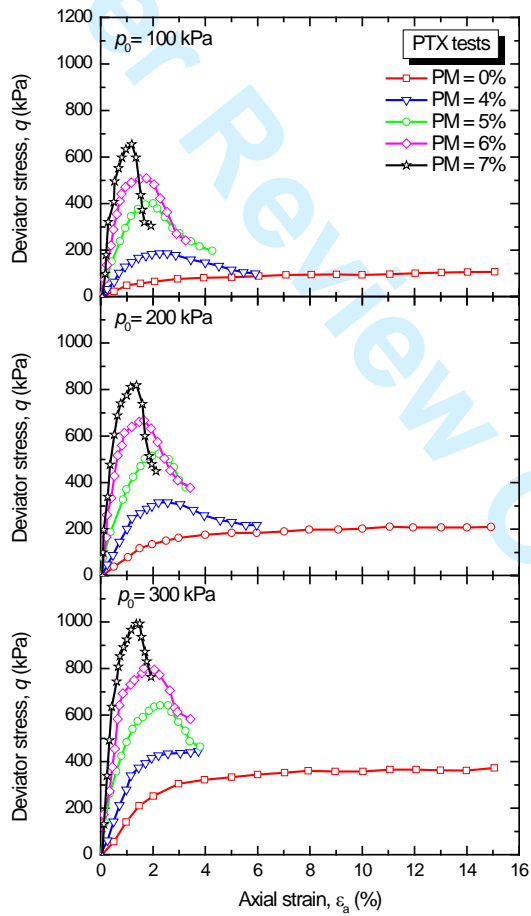


Fig. 10. Stress- strain relationships of non-solidified and solidified by PM Shanghai DM specimens in PTX tests

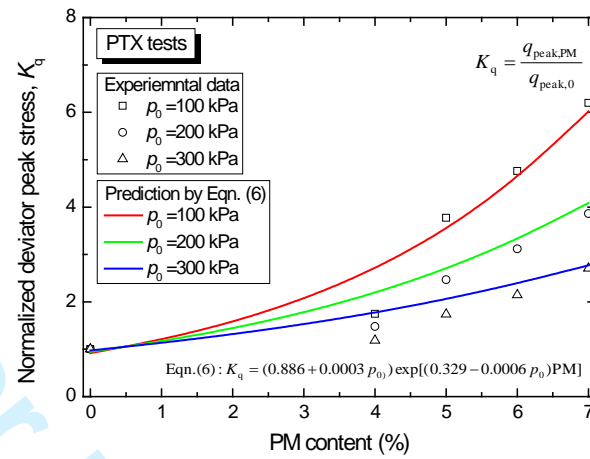


Fig. 11. Normalized peak deviator stress for Shanghai SDM in PTX tests

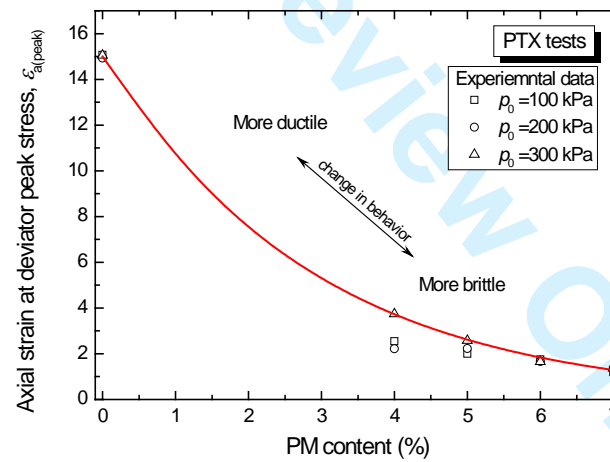


Fig. 12. Axial strain at peak deviator stress for Shanghai SDM in PTX tests

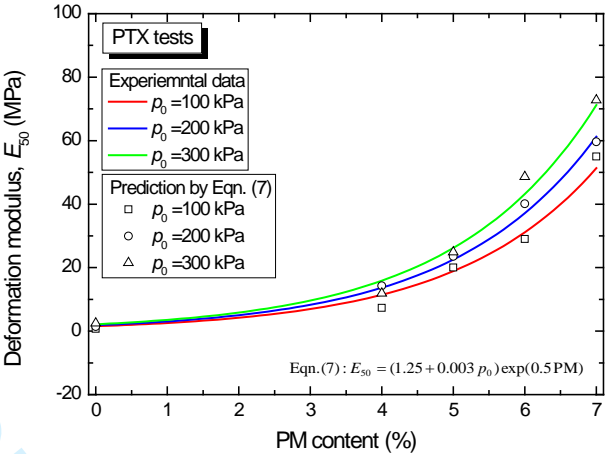


Fig. 13. Deformation modulus (E_{50}) for Shanghai SDM in PTX tests

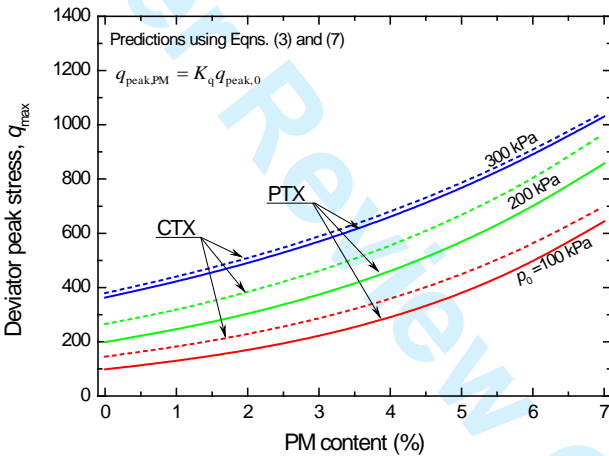


Fig. 14. Comparison between of peak deviator stress of solidified Shanghai in CTX and PTX tests